Configuration Studies for a Low-Aspect-Ratio Liquid-Metal-Wall Sustained High-Power-Density Tokamak Facility

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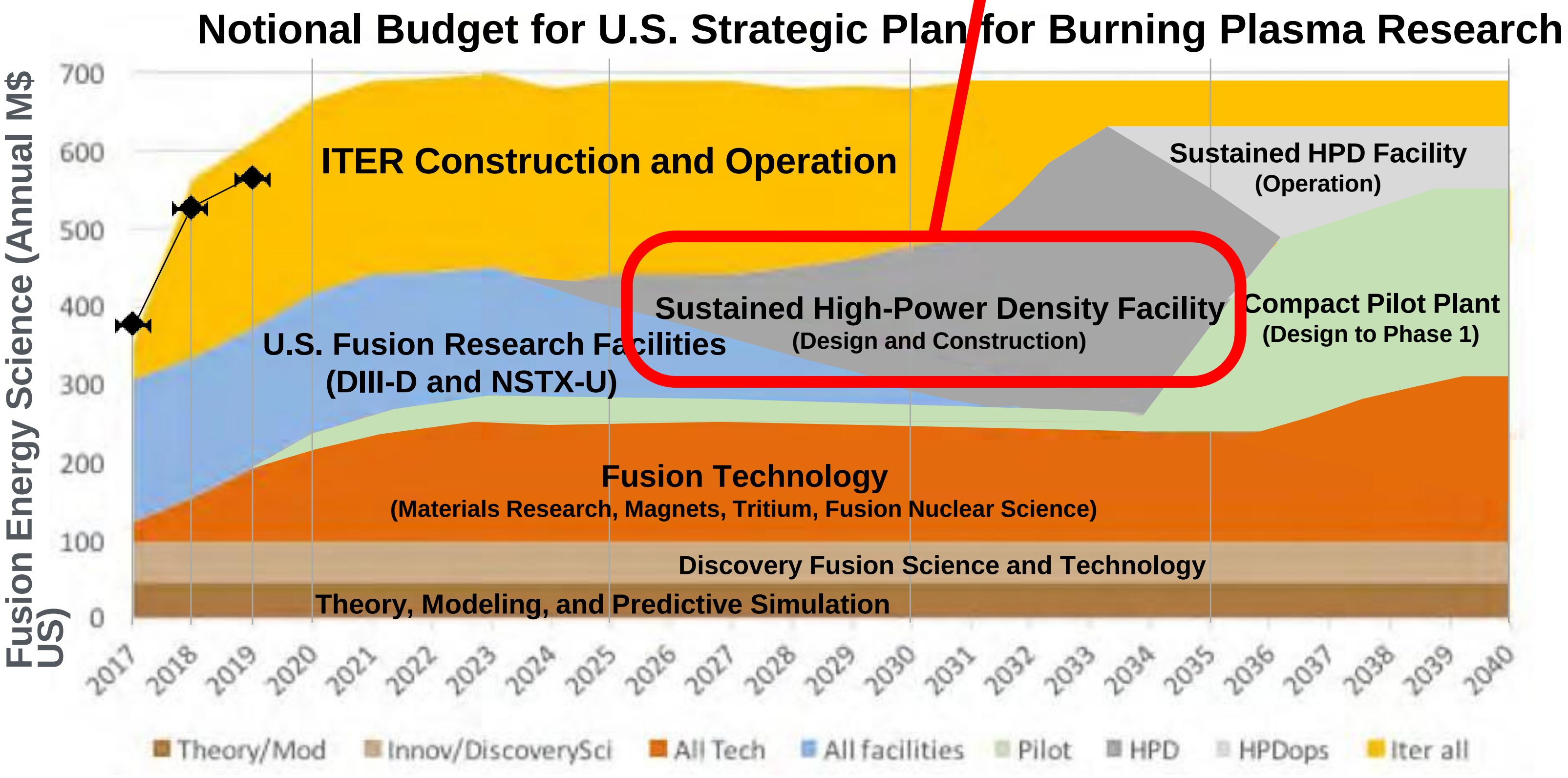
Outline

- Motivations for study
- Key core-edge integration gaps
- Configuration study results
- Summary

Recent National Academy study considered next-step Sustained High Power Density (SHPD) Facility for U.S.



The SHPD facility was described as a possible bridge to a Compact Fusion Pilot Plant (CFPP) and would either be a **new facility or an upgrade to an existing facility**

Proposed SHPD mission: bridge confinement + sustainment gap

Increase both nTτ and pulse duration 2-3 orders of magnitude

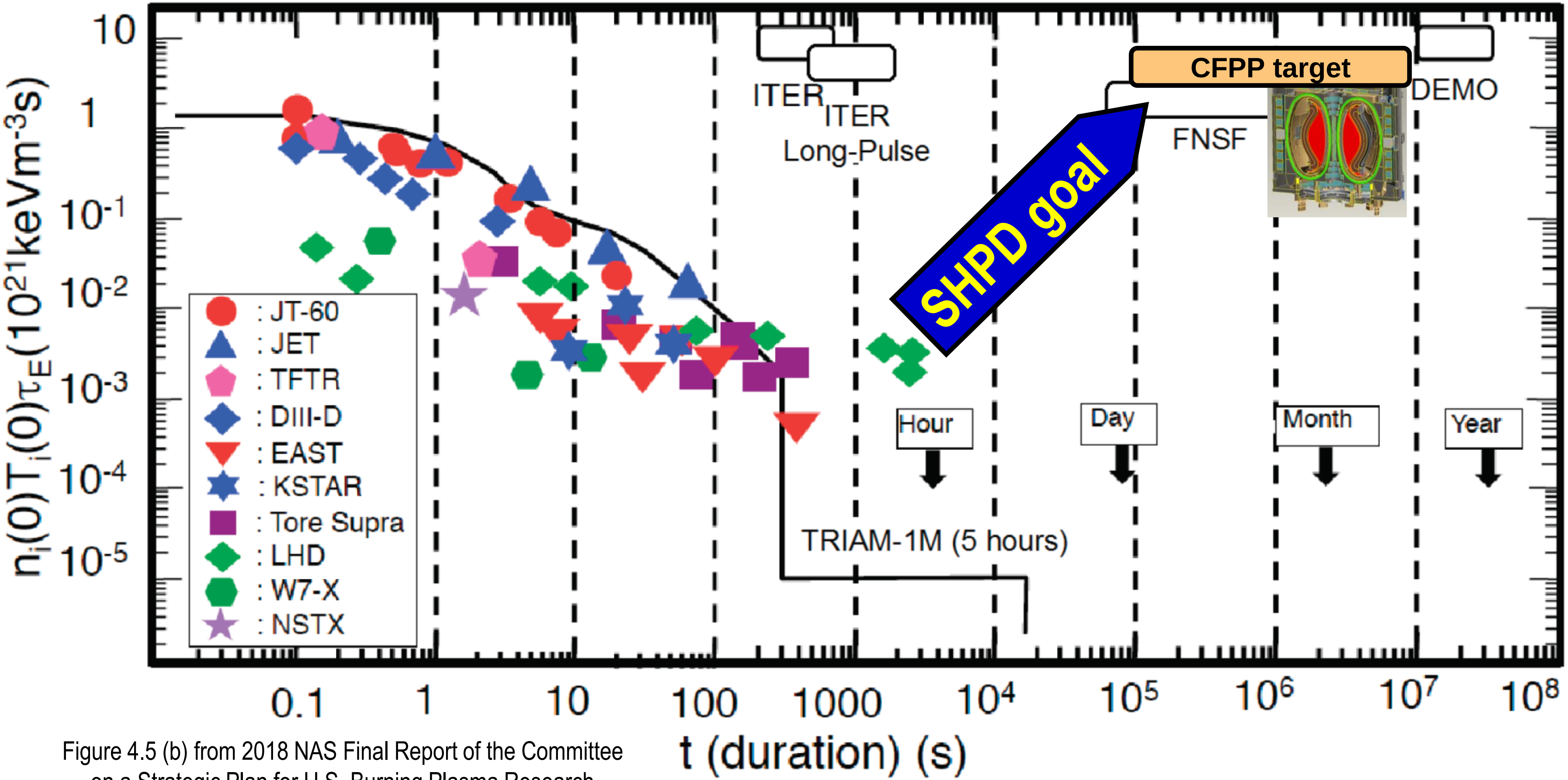


Figure 4.5 (b) from 2018 NAS Final Report of the Committee
on a Strategic Plan for U.S. Burning Plasma Research

Longest-pulse LHD plasmas terminated by C and Fe flakes after ~1 hour at P_{heat} ~ 1MW

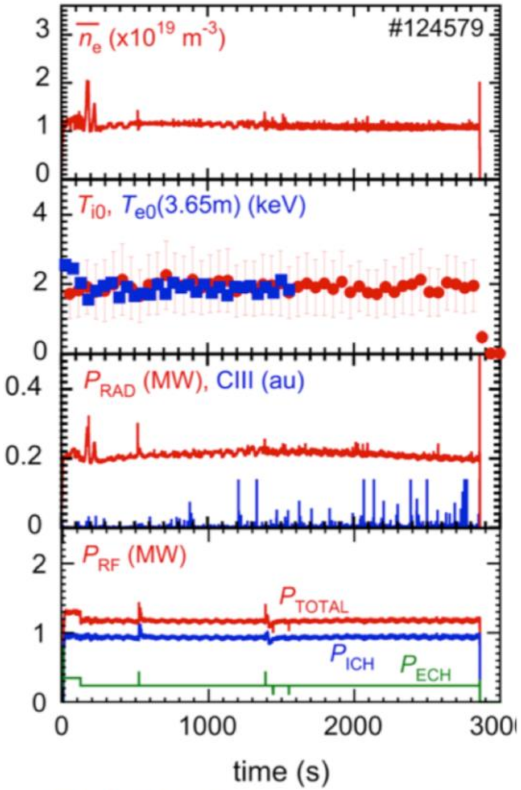


FIGURE 11. Time traces of plasma and heating parameters of 48 min operation

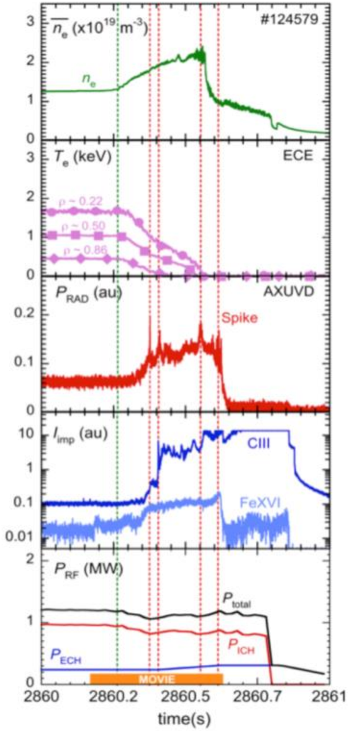


FIGURE 12. Plasma and heating parameters of termination phase of 48 min operation.

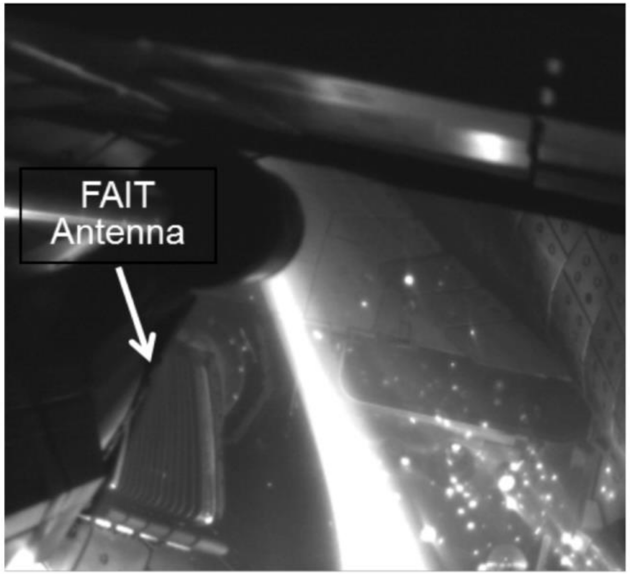
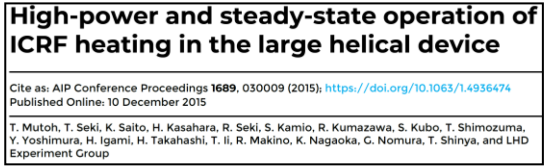


FIGURE 13. Photo of sparks near ICRF antenna of 48 min operation at termination phase


High-power and steady-state operation of ICRF heating in the large helical device

Cite as: AIP Conference Proceedings **1689**, 030009 (2015); https://doi.org/10.1063/1.4936474
Published Online: 10 December 2015

T. Mutoh, T. Seki, K. Saito, H. Kasahara, R. Seki, S. Kamio, R. Kumazawa, S. Kubo, T. Shimozuma, Y. Yoshimura, H. Igami, H. Takahashi, T. Ii, R. Makino, K. Nagaoka, G. Nomura, T. Shinya, and LHD Experiment Group

Motivations for CFPP-prototypical SHPD facility

- Integrate edge/wall solutions + high-performance core plasma
- For steady-state tokamak option, need simultaneous CFPP-relevant high plasma pressure and high bootstrap fraction
  - Pulsed tokamak reactors would have reduced bootstrap fraction required, but may have challenges with thermal & mechanical cyclic fatigue (TBD)
- CFPP-level pressure is needed to demonstrate relevant:
  - Divertor power density – to challenge divertor at CFPP-relevant levels
  - Pressure in SOL – representative detachment and control
  - First-wall erosion rate – representative mass transport and migration and *mass removal* using configuration and actuators prototypical of a CFPP
- R&D + test PFC and actuator technologies for very long-pulses with CFPP-level plasma / thermal / EM / mechanical conditions

Science and technology **Gaps** to a steady-state Compact Fusion Pilot Plant (CFPP)

Abbreviated / simplified listing of Key Gaps:

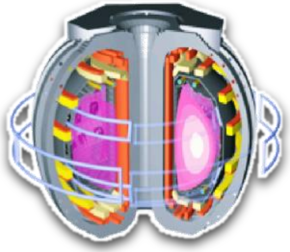
1. Access reliable sustainment of enhanced energy confinement
2. Demonstrate efficient external non-inductive current-drive methods
3. Demonstrate pilot-relevant power and particle exhaust handling
4. Demonstrate pilot-relevant first-wall, components, maintenance
5. Avoid transient events that might damage facility components
6. Develop high-current-density and high-field toroidal field magnets
7. Develop fusion-nuclear components for pilot-relevant performance

Focus of this presentation (see backup for gaps 5-7)

Gaps 1, 2: NSTX-U, DIII-D, JT-60SA well equipped to develop high-confinement, high-β, full non-inductive core scenarios

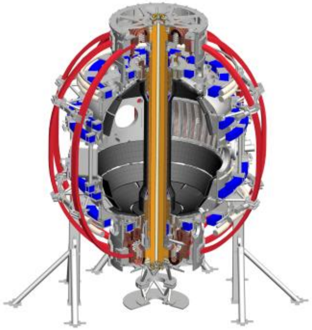
Values are representative only!

- **τ_E:** DIII-D, NSTX have demonstrated $H_{98} > 1.5$ (at least transiently), elevated H_{98} planned for JT-60SA



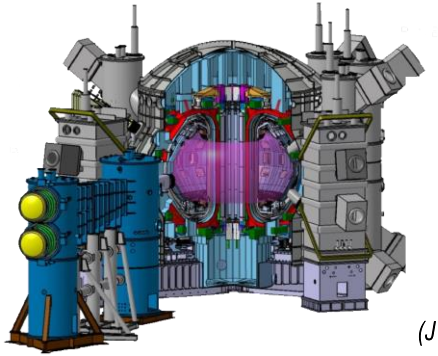
DIII-D
A = 2.5-2.8
$H_{98} = 1.3\text{-}2.0$
$\beta_N = 3.5\text{-}5$
$f_{BS} = 0.5\text{-}0.8$

- **β:** NSTX-U, DIII-D, JT-60SA utilize close-fitting passive conductors and 3D control coils to access high β_N



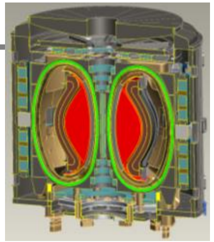
NSTX-U
A = 1.6-1.8
$H_{98} = 1.4\text{-}1.7$ for $H_{ST}\sim1$
$\beta_N = 4\text{-}6$
$f_{BS} = 0.5\text{-}0.8$
(NSTX-U physics design, NF 2012)

- **J_{NI}:** All 3 have on and off-axis CD for current profile variation with full non-inductive with elevated $f_{BS} > 70\%$



JT60-SA
A = 2.5-2.7
$H_{98} = 1.3\text{-}1.4$
$\beta_N = 4\text{-}4.5$
$f_{BS} = 0.7\text{-}0.8$
(JT-60SA Research Plan v4.0)

Gap 3: Example power exhaust parameters



From R. Goldston - Plasma Phys. Control. Fusion 59 (2017) 055015

Parameter / Device	C-Mod	AUG	JET	ITER	FNSF (A=4)	EU Demo1	Low-A PP	ARC
Aspect Ratio A	3.2	3.1	3.2	3.1	4.0	3.1	2.0	3.0
P_{sep} [MW]	3.83	10.7	14	100	96	154.7	100.0	95.3
B_T [T]	5.47	2.5	2.5	5.3	7	5.7	4.0	9.2
R_0 [m]	0.7	1.6	2.9	6.2	4.5	9.1	3.0	3.3
P_{sep} / R [MW / m]	5.5	6.7	4.8	16.1	21.3	17.0	33.3	28.9
$P_{sep}B_T$ / R [MW T / m]	30.1	16.8	12.0	85.3	149.1	96.9	133.3	265.8
I_P [MA]	0.82	1.2	2.5	15	7.5	20	12.5	7.8
a [m]	0.22	0.52	0.9	2	1.13	2.94	1.5	1.1
κ_{95}	1.51	1.63	1.73	1.8	2.1	1.7	2.25	1.66
$\langle B_p \rangle$ [T]	0.58	0.34	0.39	1.03	0.81	0.98	0.90	0.97
q_{cyl}	3.78	3.16	2.79	2.42	3.55	2.62	4.35	4.74
n_{GW} [$10^{20}m^{-3}$]	5.39	1.41	0.98	1.19	1.87	0.74	1.77	2.05
Projected c_N for detachment	1.0%	4.0%	4.1%	10.1%	8.6%	18.8%	6.6%	12.2%

ITER
FNSF
EU-Demo1
CFPP:

16-33

85-266

0.8-1

6-19%

Assume same simple fixed n_{sep} / n_{GW} scaling from ASDEX-U

Gap 3: Example power exhaust parameter gaps

Parameter / Device	NSTX-U I_P=2MA	NSTX-U I_P=1MA	DIII-D I_P=2MA	DIII-D I_P=1MA	JT-60SA (Inductive)	JT-60SA (Fully Non-Inductive)	Divertor Test Tokamak (Italy DTT)	SPARC	Low-A Pilot Plant	ARC
Aspect Ratio A	1.7	1.7	2.8	2.8	2.5	2.7	3.1	3.3	2.0	3.0
P_{sep} [MW]	12.7	12.7	16.7	16.7	27.3	24.7	32.0	30.0	100.0	95.3
B_T [T]	1	1	2.1	2.1	2.25	1.72	6	12	4	9.2
R_0 [m]	0.94	0.94	1.6	1.6	2.96	2.97	2.15	1.65	3	3.3
P_{sep} / R [MW / m]	13.5	13.5	10.4	10.4	9.2	8.3	14.9	18.2	33.3	28.9
$P_{sep}B_T$ / R [MW T / m]	13.5	13.5	21.9	21.9	20.8	14.3	89.2	218.2	133	266
I_P [MA]	2.0	1.0	2.0	1.0	5.5	2.3	6.0	7.5	12.5	7.8
a [m]	0.55	0.55	0.58	0.58	1.18	1.11	0.70	0.50	1.50	1.10
κ_{95}	2.25	2.25	1.89	1.89	1.72	1.83	1.71	1.71	2.25	1.66
$\langle B_p \rangle$ [T]	0.39	0.20	0.43	0.21	0.62	0.27	1.19	2.07	0.90	0.97
$B_{p\text{-}mp}$ [T]	0.72	0.36	0.78	0.39	1.12	0.50	2.16	3.77	1.64	1.76
λ_q [mm] (Eich NF2013 Reg #14)	1.91	4.35	1.74	3.96	1.12	2.96	0.51	0.26	0.71	0.66
$\lambda_{q\text{-}int}$ [mm]	3.41	7.79	3.11	7.09	2.00	5.30	0.92	0.47	1.27	1.18
$q_{\|\|0}$ [GW / m^2]	1.3	1.2	2.2	1.9	2.2	1.3	10.8	29.5	15.4	31.1
n_{GW} [$10^{20}m^{-3}$]	2.10	1.05	1.89	0.95	1.26	0.59	3.90	9.55	1.77	2.05
Projected c_N for detachment	1.9%	3.9%	3.6%	7.2%	5.0%	8.9%	3.1%	1.7%	6.6%	12.2%

Assume same simple fixed n_{sep} / n_{GW} scaling from ASDEX-U

P B_T / R (and $q_{||}$) 10x higher in CFPPs than accessible in existing/ near-term devices, but iDTT, SPARC access CFPP-relevant values

Lower-I_P JT-60SA (and DIII-D) scenarios access CFPP-relevant detachment regime

PFC survivability during any off-normal re-attachment events is major concern for CFPP (see Goldston vapor box work)

Gap 4: Projected first-wall erosion in EU-DEMO / CFPP

An assessment for the erosion rate of DEMO first wall **- M.Z. Tokar**

Nucl. Fusion **58** (2018) 016016

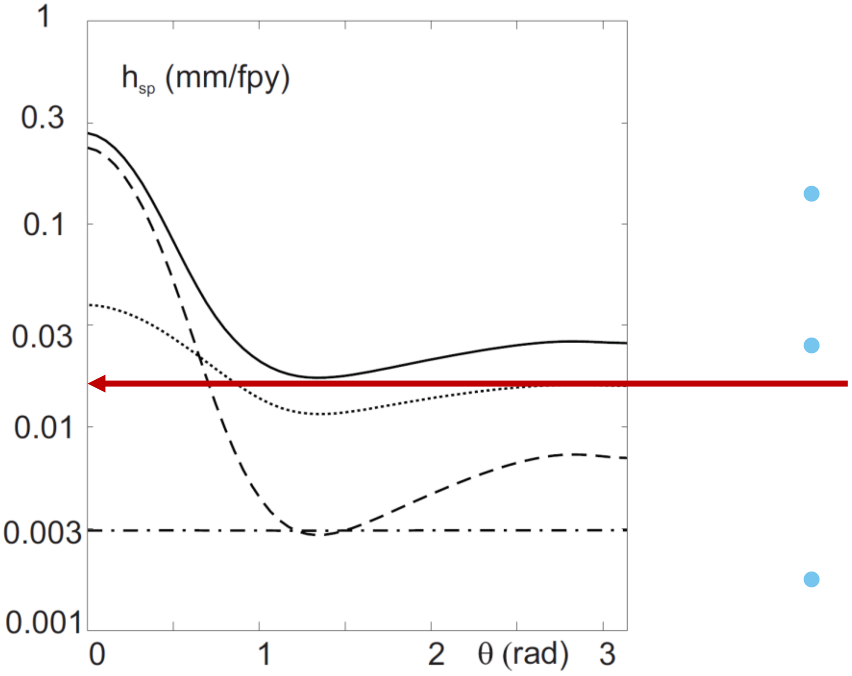


Figure 5. The poloidal profile of the wall erosion rate (solid line) and contributions to it from c-x atoms (dashed line), highly charged impurity ions (dotted line) and the main ions during ELMs (dashed-dotted line).

- Erosion largest on outboard
  - 0.2-0.3mm / fpy peak outboard
  - Charge-exchange dominates
  - 10x lower on top / bottom / inboard
- Highly charged impurity ions dominant top / bottom / inboard
- **0.02 mm / fpy corresponds to ~1.6 kg of W per day**
- CFPP first-wall surface area is ~15-30% of EU-DEMO:
  - **0.2-0.5 kg / day W for R=3m A=2-3 HTS Pilot Plant (P_{fus} ~ 500MW)**

Gap 4: Erosion sensitive to transport, outboard gap

Investigations of the first-wall erosion of DEMO with the CELLSOR code

M. Beckers et al. / Nuclear Materials and Energy 12 (2017) 1163–1170

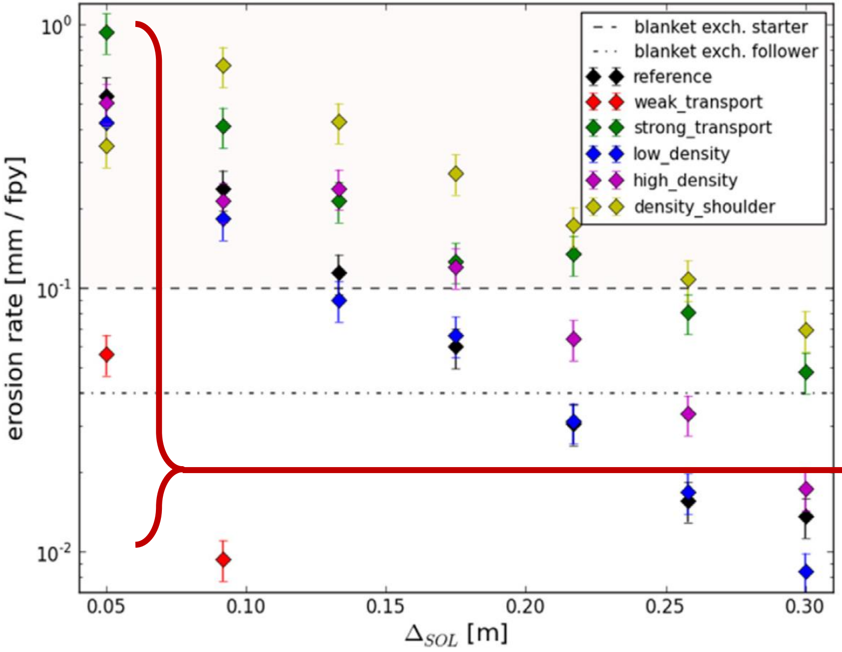


Fig. 6. Net erosion rate in mm/fpy by ions (D, T, He, N, W) and neutrals (D, T) for the 6 SOL test cases (Table 2).

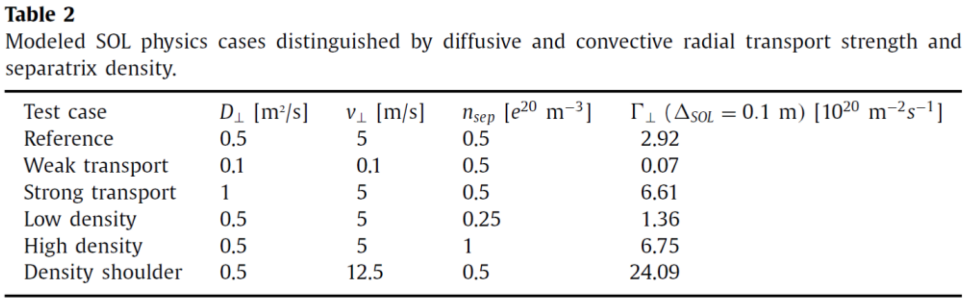


Table 2
Modeled SOL physics cases distinguished by diffusive and convective radial transport strength and separatrix density.

Test case	$D_\perp$ [m^2/s]	$v_\perp$ [m/s]	n_{sep} [e^{20} m^{-3}]	$\Gamma_\perp$ ($\Delta_{SOL} = 0.1$ m) [10^{20} $m^{-2}s^{-1}$]
Reference	0.5	5	0.5	2.92
Weak transport	0.1	0.1	0.5	0.07
Strong transport	1	5	0.5	6.61
Low density	0.5	5	0.25	1.36
High density	0.5	5	1	6.75
Density shoulder	0.5	12.5	0.5	24.09

- Low transport or large gaps can reduce risk to PFCs, but…
- **0.01-1 mm / fpy → 0.8-80 kg W erosion / day (EU-DEMO)**
- What is impact of erosion?
  - Dust formation, T retention?
  - Impact on core plasma, radiation?
  - Transported to divertor? other?

Erosion projections and results reinforce need for significant improvement in research capability

- Independent of the magnetic configuration, need to develop and demonstrate very long-pulses at high performance with no mass accumulation / plasma termination
  - Pulse lengths of at least 1 hour to 1 day likely required to gain confidence in solutions

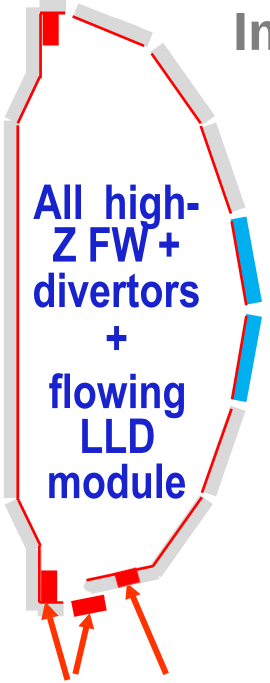
- Need facility that can demonstrate active mass removal from eroded divertor and/or first-wall

- Liquid metals may offer a solution for self-healing walls and flow-through removal of solid divertor/wall eroded materials

After characterizing low-ν^* + high-β ST performance with C PFCs, NSTX-U will play important role in high-Z + liquid metal PFC R&D

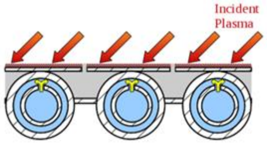
- NSTX-U intends to transition to all high-Z PFCS
  - Avoid carbon, due to formation of compounds that contaminate Li (LTX, NSTX LLD experience)
  - Incorporate coming LTX-β results on high τ_E, flat T_e profiles, importance of liquid vs solid walls
- Low heat flux regions would have pre-filled tiles or evaporated coatings for particle control
  - Cryo-pump could be installed as a future option for a detailed comparison with Li pumping
- High heat flux regions would have flowing liquid lithium module(s) for power exhaust
- Measure erosion, re-deposition, mass transport to/from FW and divertor → inform SHPD, CFPP
- Collaborate with and inform new FES LM PFC Development Program

Implement ≥ 2025
(Phase 2)

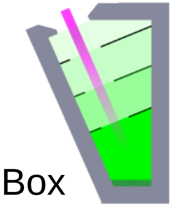


All high-Z FW + divertors + flowing LLD module

Flowing Li module
(Concept, location, size TBD)



CPS



Vapor Box

Outline

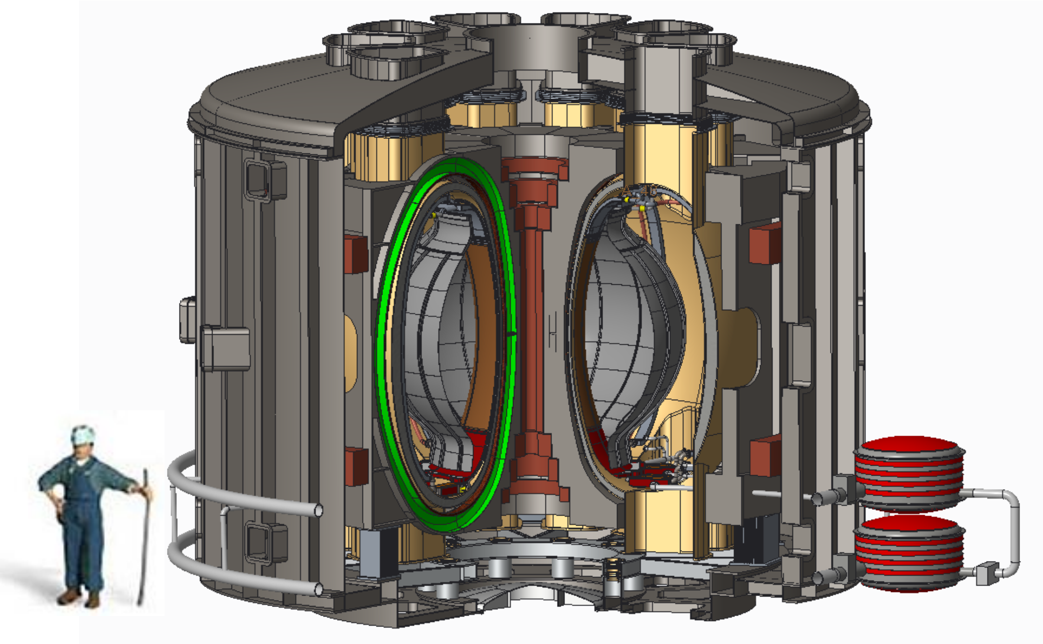
- Motivations for study
- Key core-edge integration gaps
- Configuration study results
- Summary

Range of SHPD configurations being investigated

- Assessing R=1 to 2m, A=2-2.6 (A=2.4 for detailed layouts)
- Detailed layouts developed for R=1.0m, 1.2m

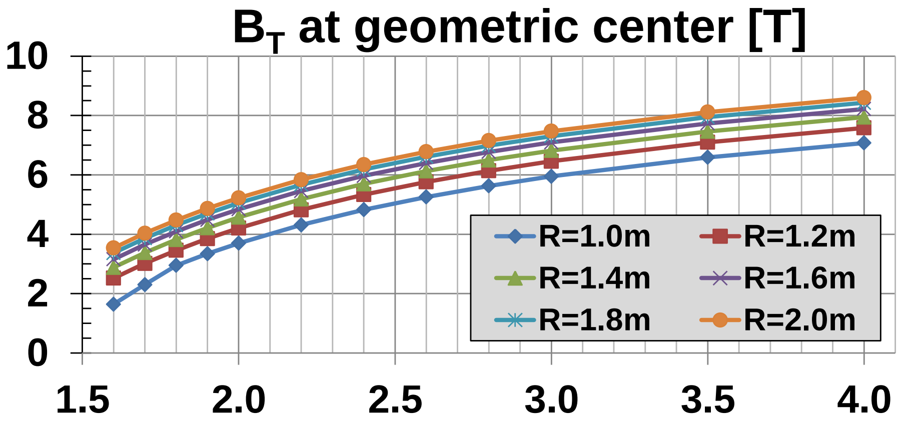
Key features:

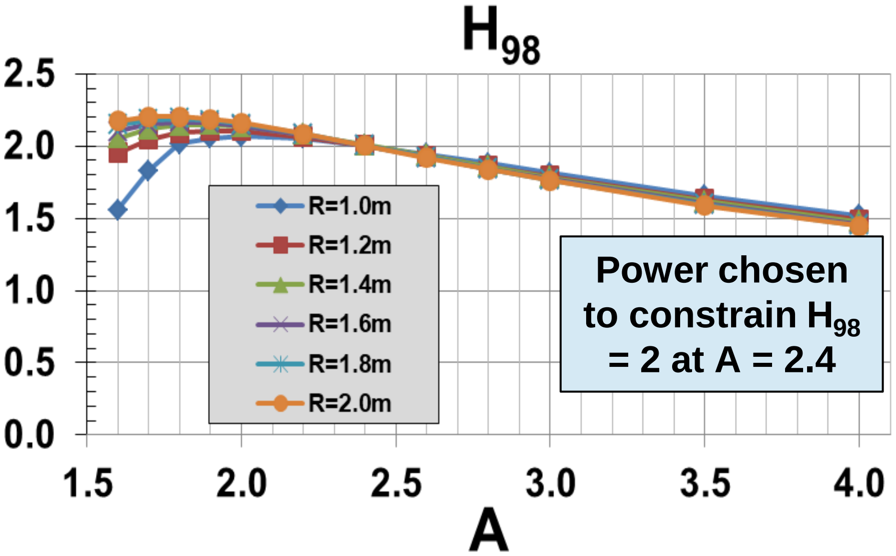
- Flexible exhaust config.
  - Solid and liquid metal PFCs
  - Vertical target, long-leg div.
  - Double null capability
- High current density TF and inboard PF coils
- Vertical maintenance
- B_T = 4-7T field at R_0



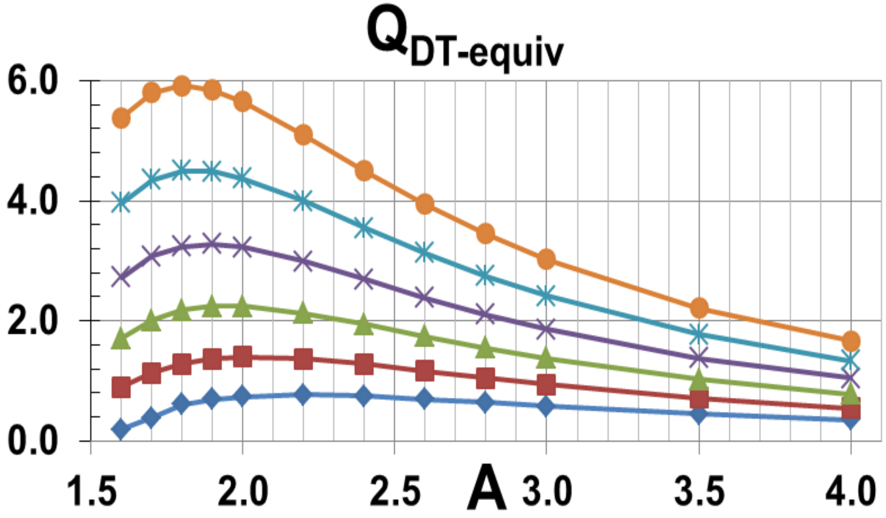
R=1.0m, A=2.4

Scoping studies for SHPD performance vs. A and R





Power chosen to constrain H_{98} = 2 at A = 2.4



Heating power depends on R, independent of A

R [m]	1.0	1.2	1.4	1.6	1.8	2.0
P_{heat} [MW]	23.5	37	52	70	89	110

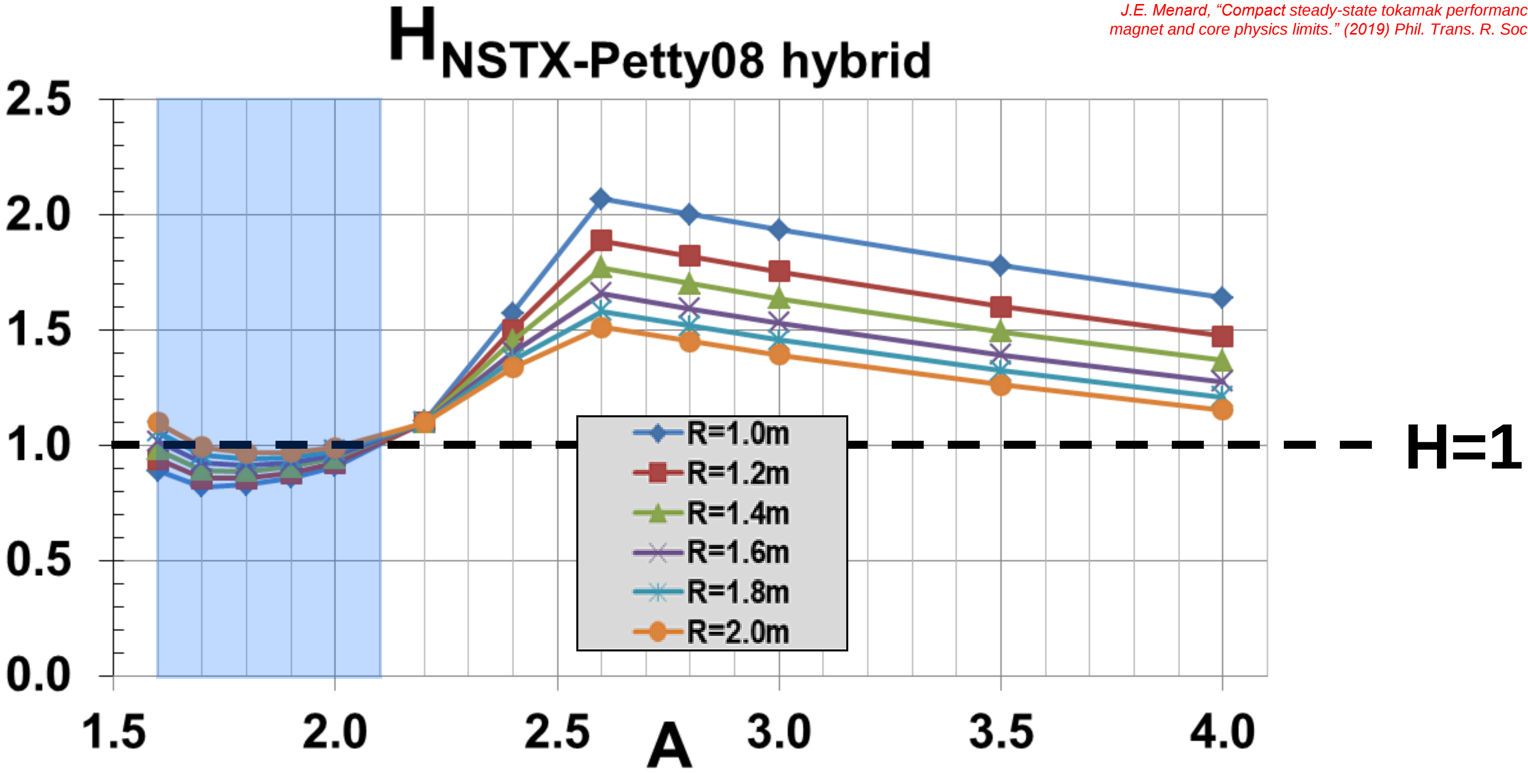
A = 1.6 - 2.1 potentially advantageous for confinement

Assume confinement time is weighted sum (vs $\varepsilon = A^{-1}$) of NSTX and Petty-08 scalings:

$\varepsilon \geq \varepsilon_1 \rightarrow \tau_E = \tau_{E\text{-NSTX}}$ $\quad\quad$ $\varepsilon \leq \varepsilon_2 \rightarrow \tau_E = \tau_{E\text{-Petty-08}}$

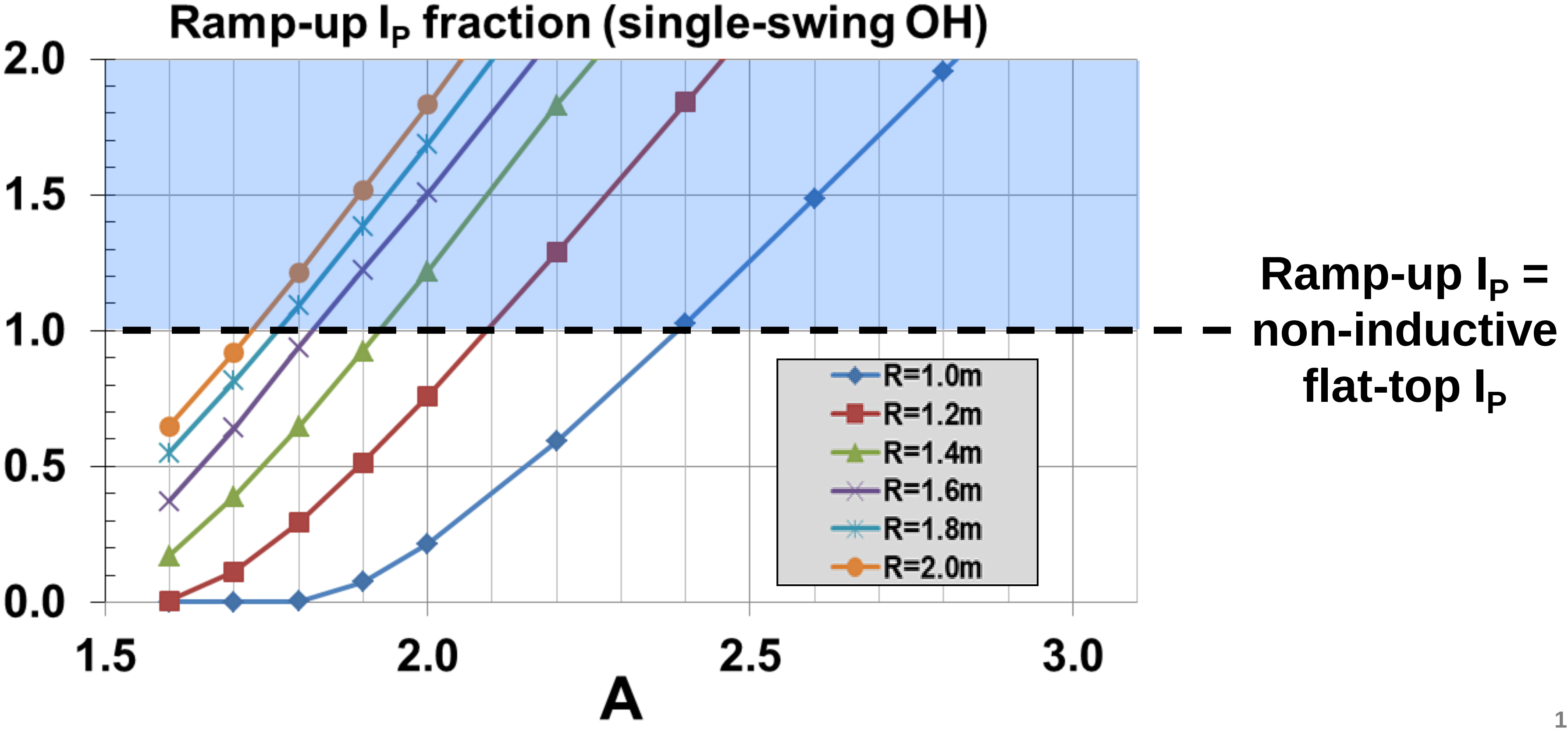
$\varepsilon_1 > \varepsilon > \varepsilon_2 \rightarrow \tau_E = (\varepsilon-\varepsilon_2)/(\varepsilon_1-\varepsilon_2)\, \tau_{E\text{-NSTX}} + (\varepsilon_1-\varepsilon)/(\varepsilon_1-\varepsilon_2)\, \tau_{E\text{-Petty-08}}$

J.E. Menard, "Compact steady-state tokamak performance dependence on magnet and core physics limits." (2019) Phil. Trans. R. Soc. A 377: 20170440.



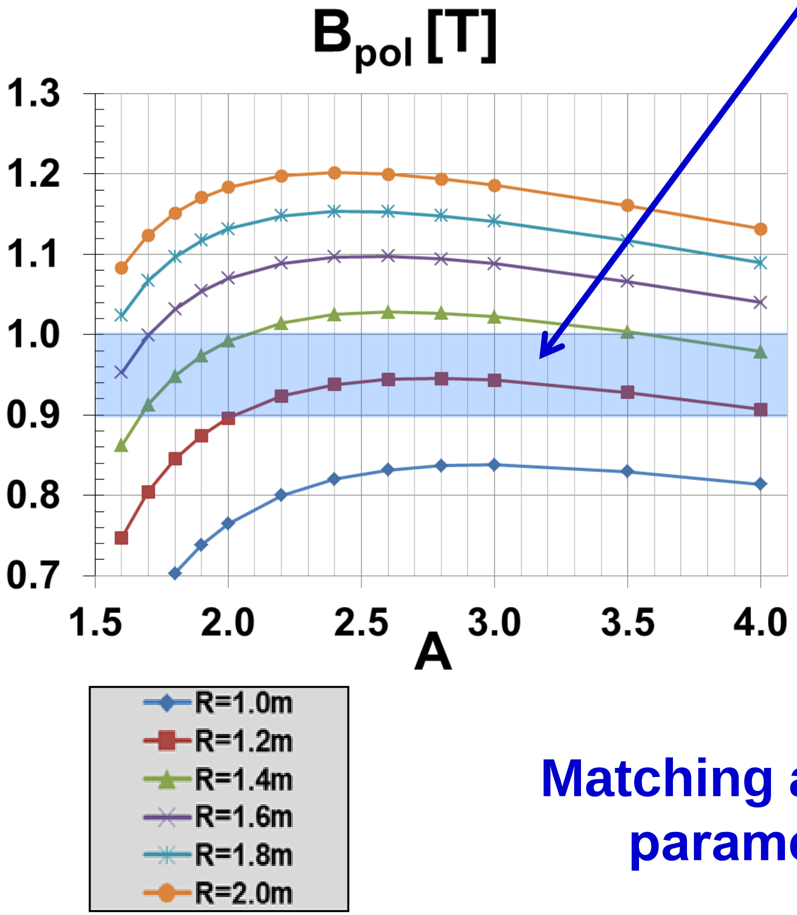
Need R ≥ 1.2m for OH-assisted ramp-up at A ~ 2

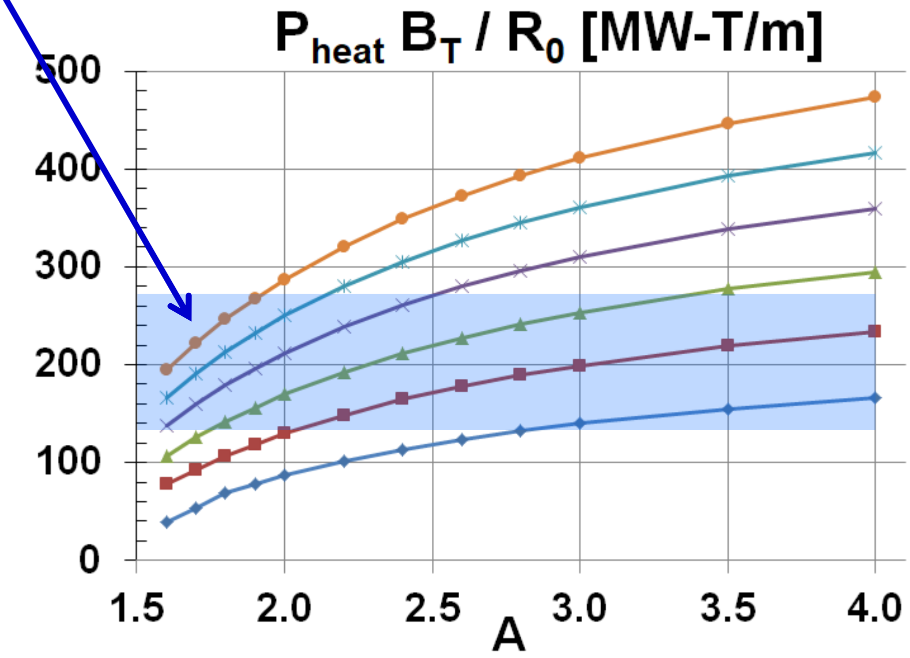
- **Smaller R at A ~ 2 does not provide sufficient space for solenoid for ramp-up**
- **R ≥ 1.2m, A ≥ 2 can access I_P ≥ 1.4x higher than non-inductive value**



Scaling of 0D power exhaust parameters

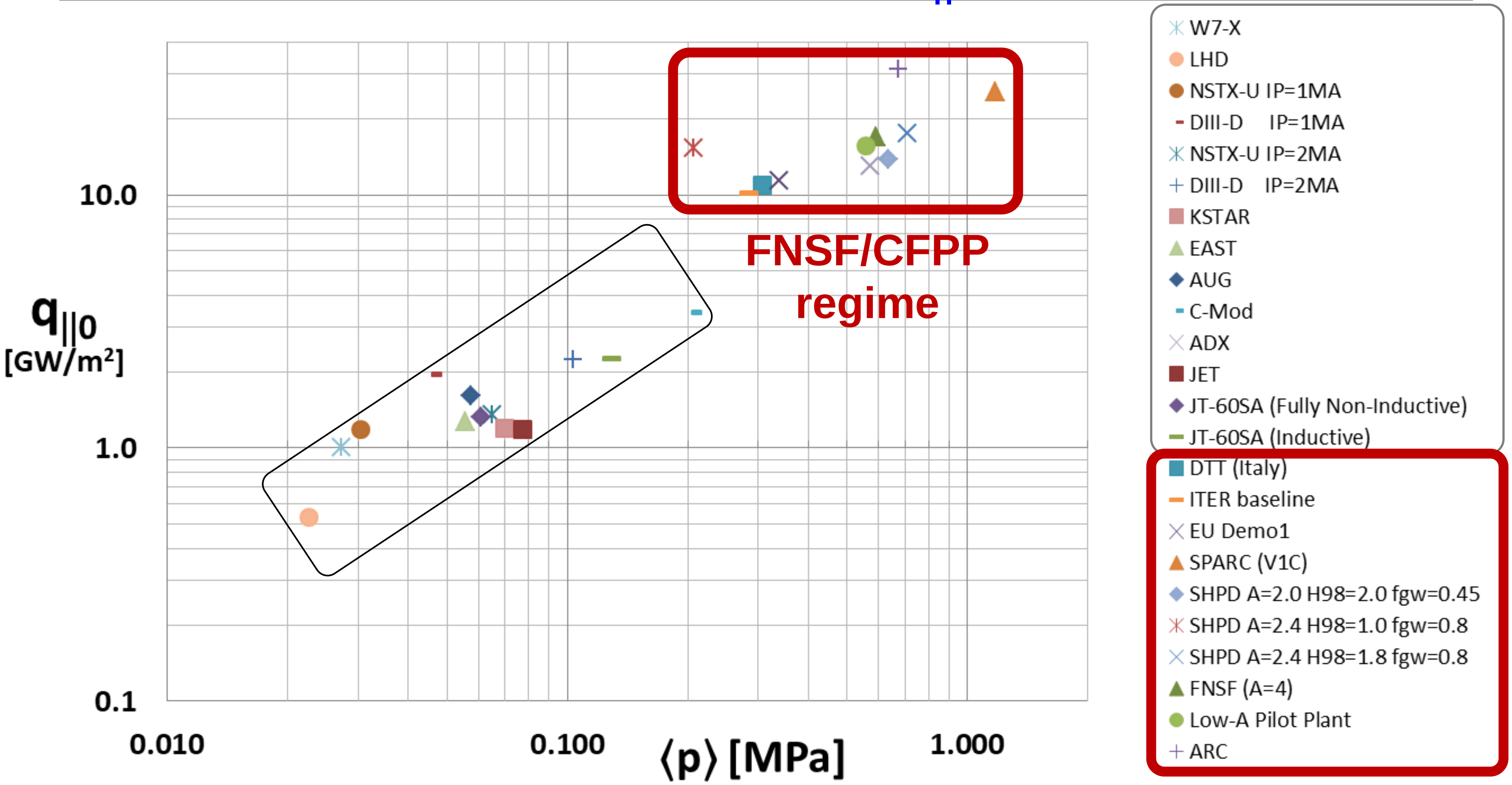
CFPP Range





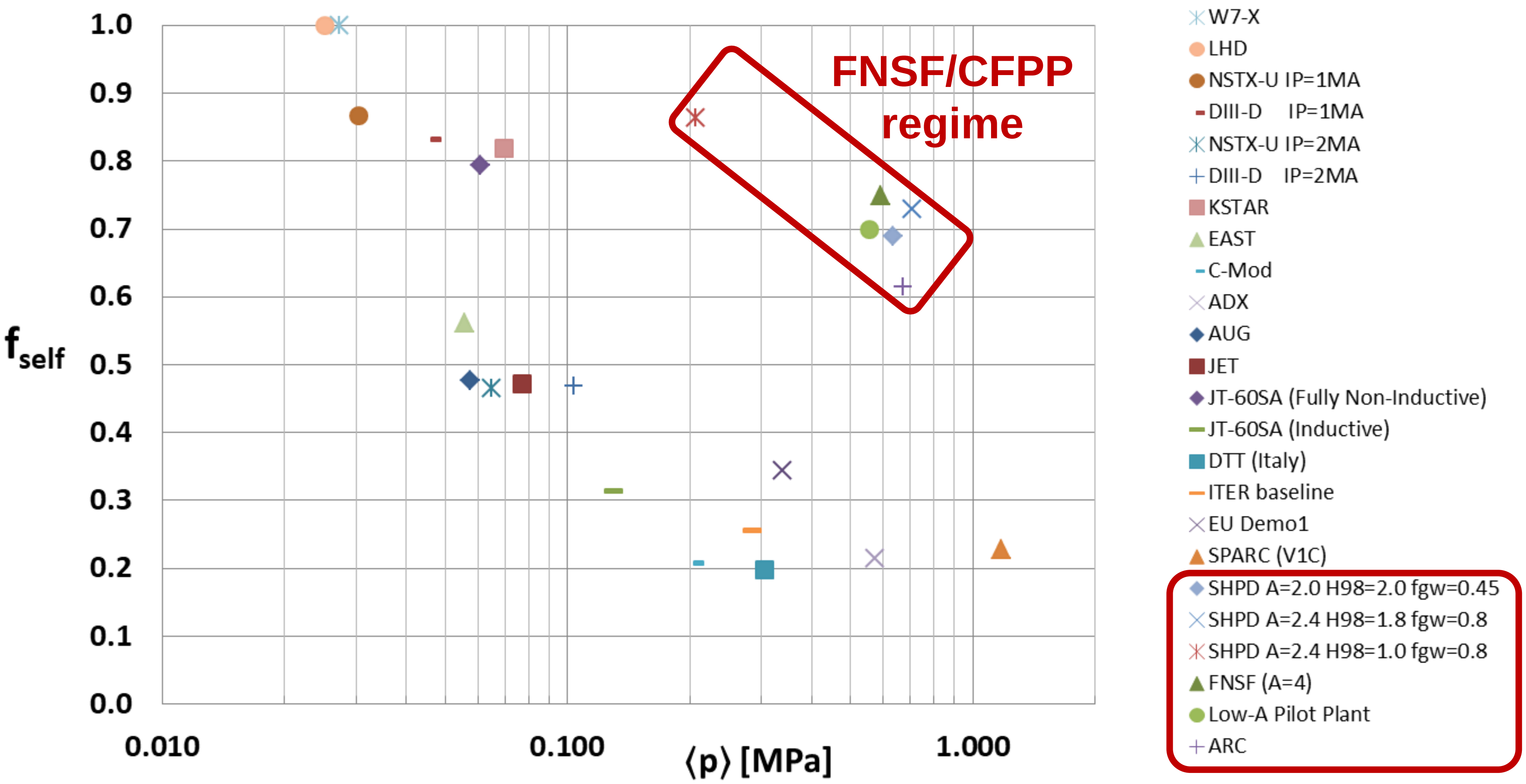
Matching above CFPP 0D power exhaust parameters drives SHPD R ≥ 1.2m

Several planned / proposed devices projected to access high pressure and $q_{||0}$ of FNSF/CFPP

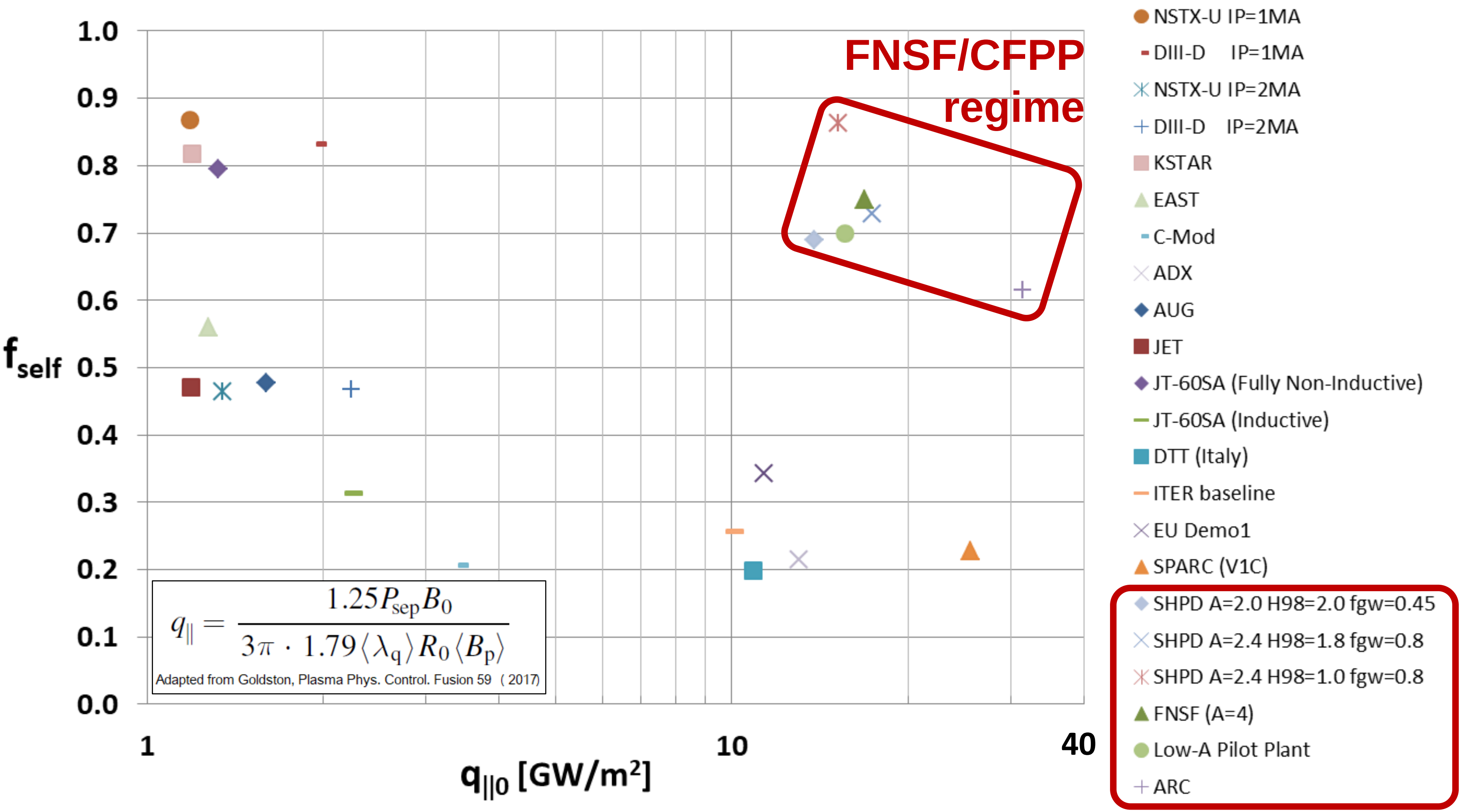


FNSF/CFPP regime

SHPD with R=1.2m, A=2-2.4, 50MW provides unique access to high pressure + high-f_{BS} regime for steady-state FNSF/CFPP



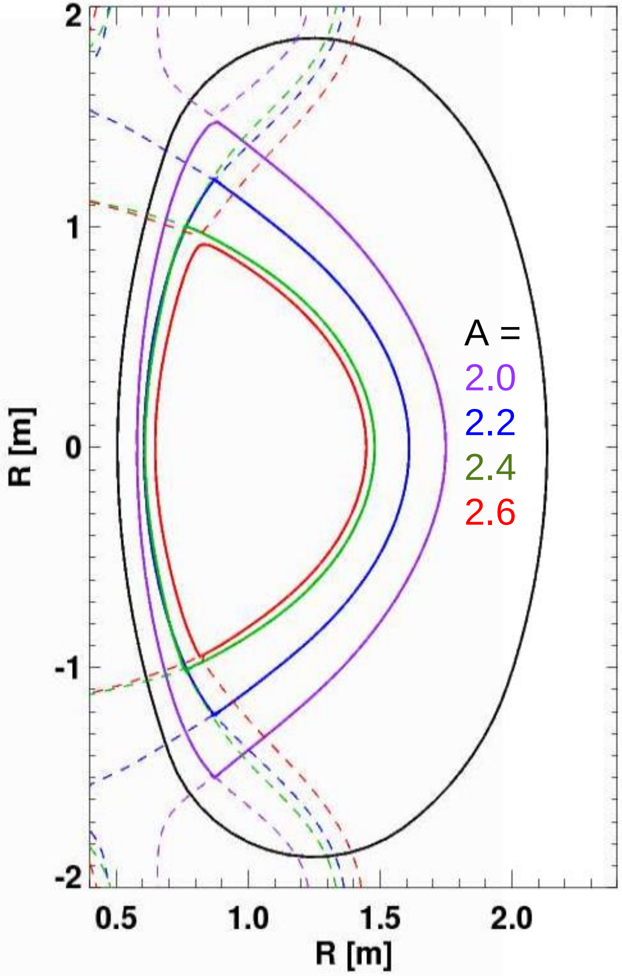
SHPD with R=1.2m, A=2-2.4, 50MW provides unique access to high $q_{||0}$ + high-f_{BS} regime for steady-state FNSF/CFPP



$$q_{\|} = \frac{1.25 P_{\mathrm{sep}} B_0}{3\pi \cdot 1.79 \langle \lambda_q \rangle R_0 \langle B_p \rangle}$$

Adapted from Goldston, Plasma Phys. Control. Fusion 59 (2017)

Exploring designs that can study range of A



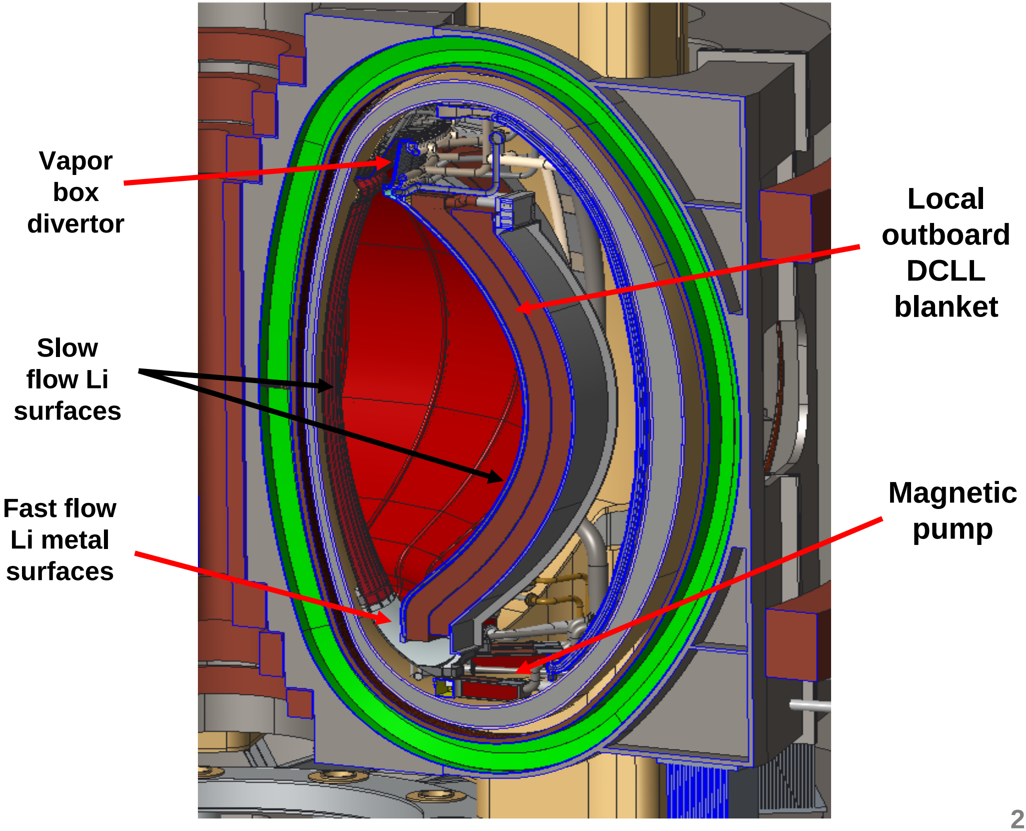
- Range of aspect ratios (A=2-2.6) supportable in single vessel
- Working to optimize vessel shape to allow κ=2.5 at A=2, lower κ at higher A
- Coil current density in inner divertor increases to high values for highest A
  - Need to increase CX area of inboard divertor coils to handle current
- Divertor strike-points have significant spatial variation – would need to change-out divertor/FW for lower A-s

Liquid metal systems included up-front in design

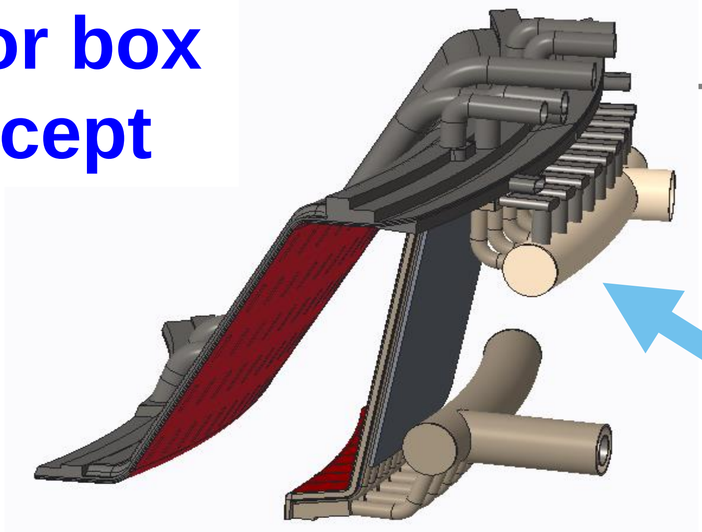
Facilities designed for other missions may not be compatible with integrated capabilities needed for U.S. CFPP vision

- Cross-sectional image of R=1m, A=2.4 SHPD concept capable of testing:
  - vapor box divertors
  - slow-flow LM first-walls
  - fast-flow LM divertors
  - DCLL test blankets

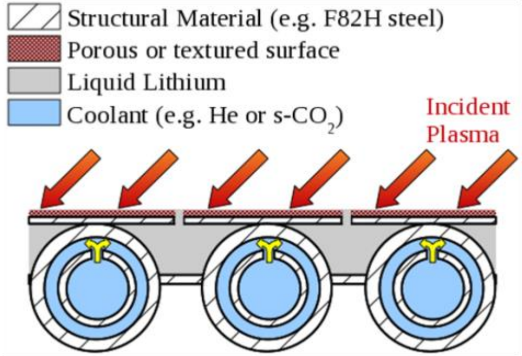
…potentially simultaneously



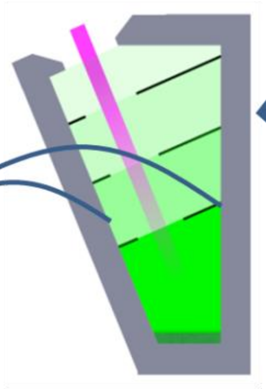
Example vapor box divertor concept



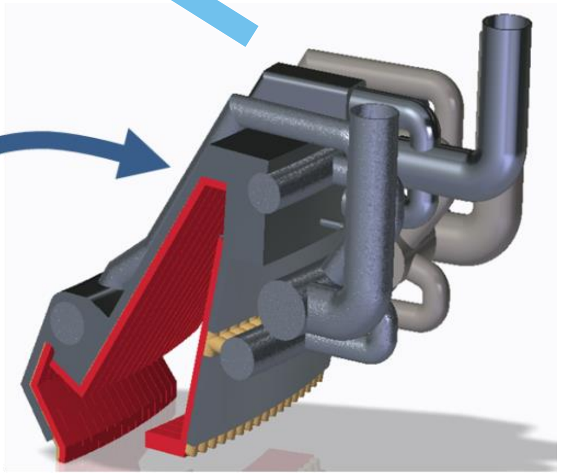
The vapor box is still evolving, more to follow



a) Schematic diagram of the actively-supplied, capillary-restrained system

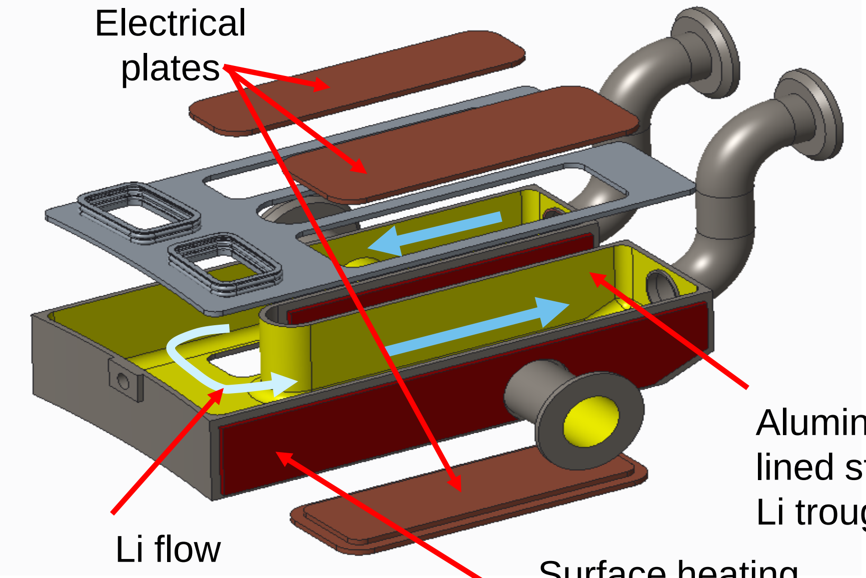


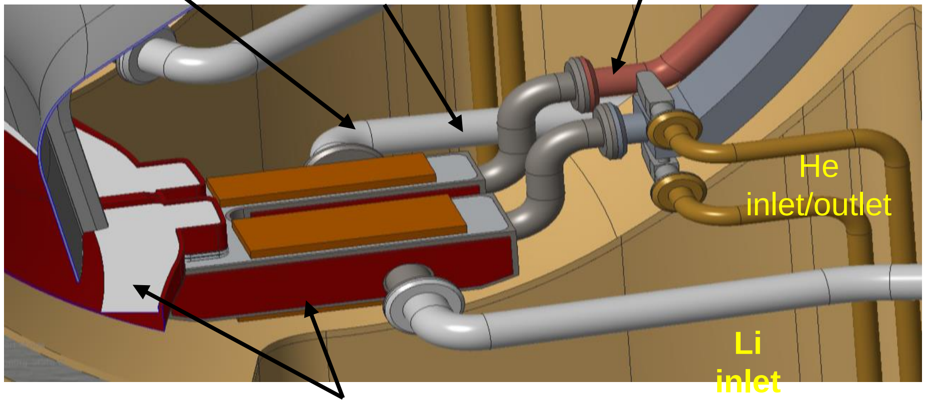
b) Vapor box divertor

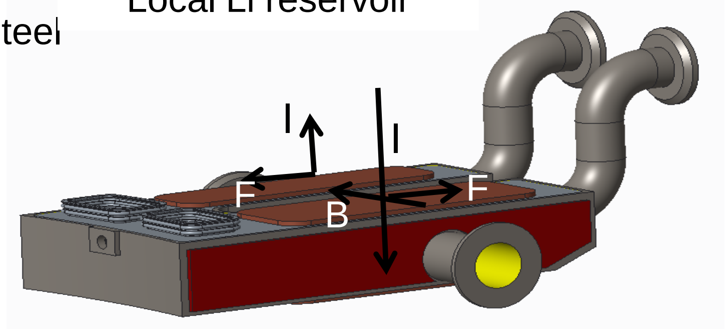


c) T-tube heat exchanger design concept

Example Li magnetic pump system for fast flow

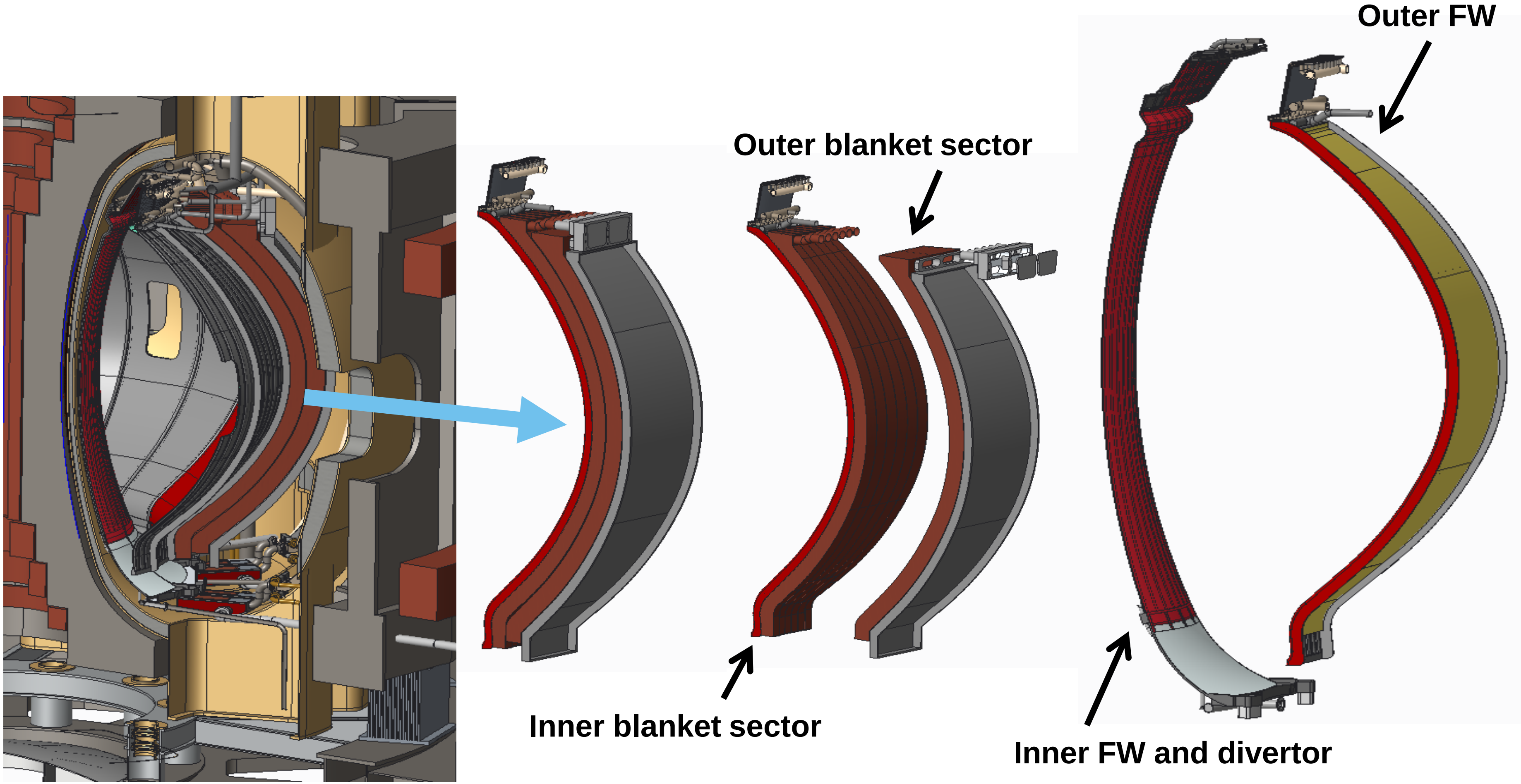






Magnetic pump

Example modular first-wall structures, blankets, supports for LM technology development flexibility

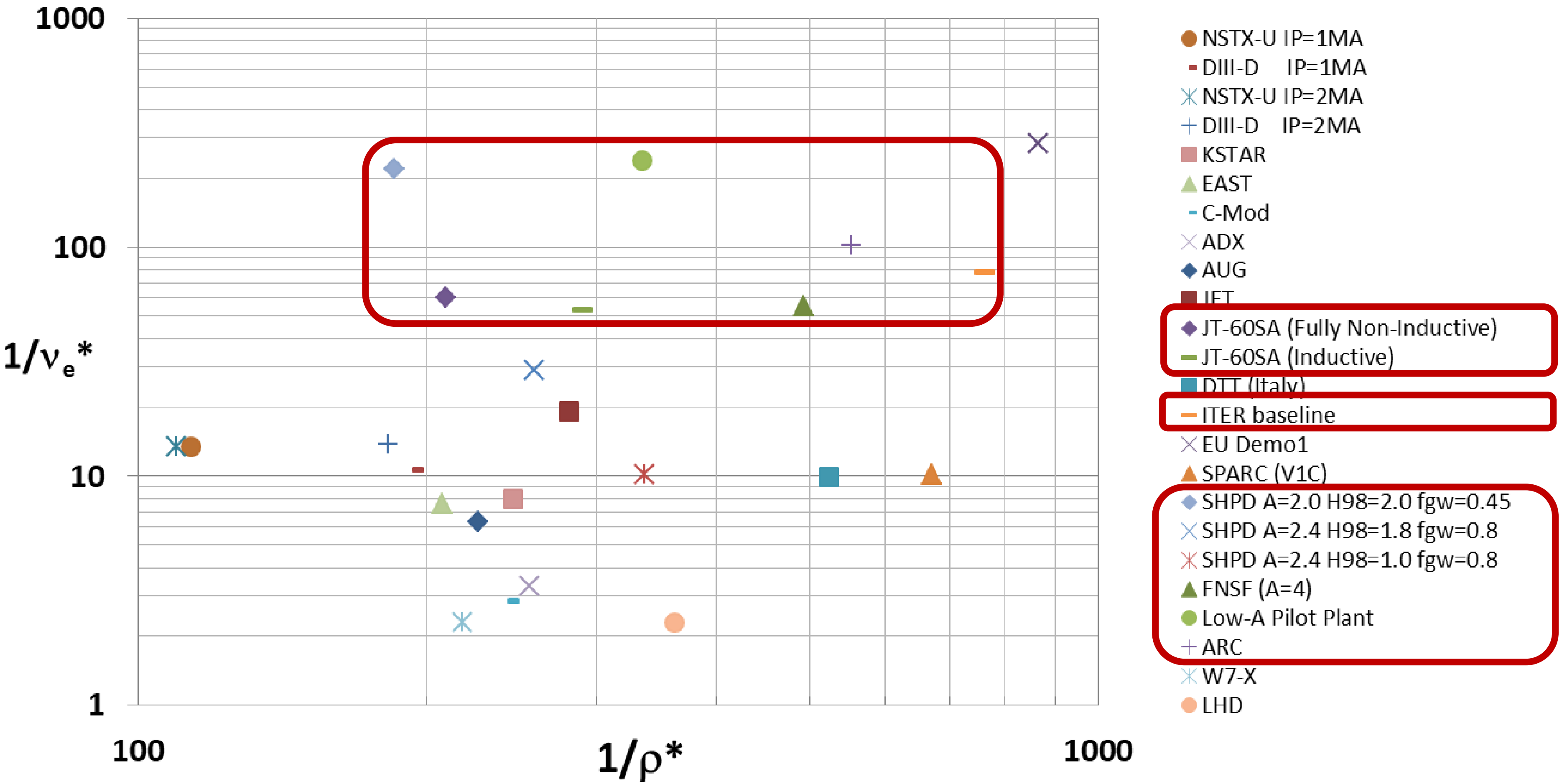


Summary: SHPD would close core-edge integration physics and technology gaps to steady-state CFPP

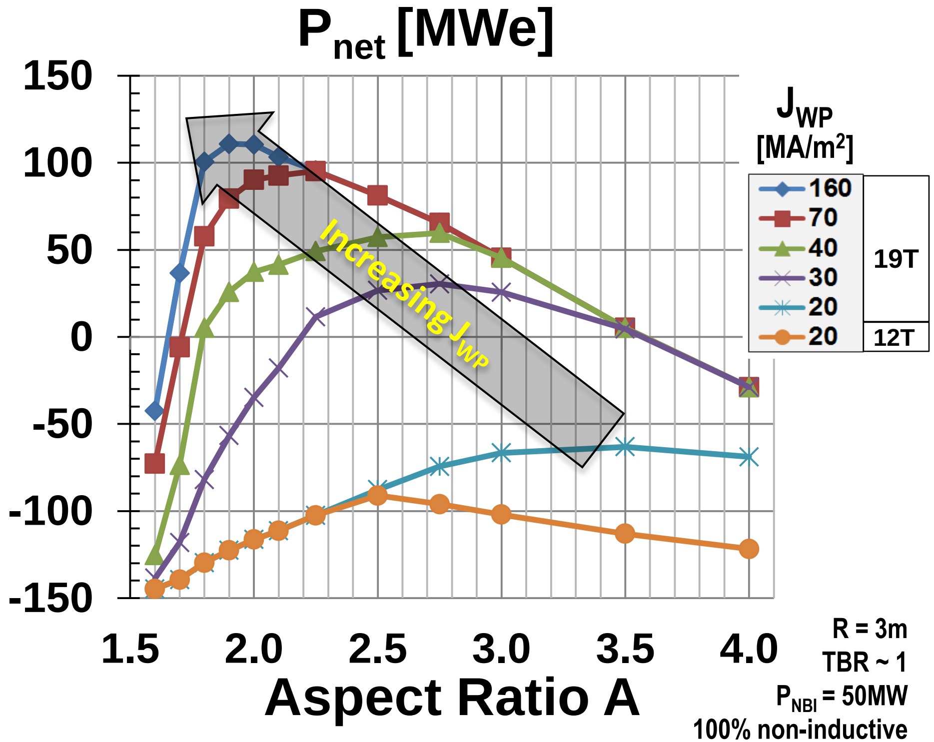
- Unique access to simultaneous ⟨p⟩, $q_{||}$, f_{BS} of steady-state CFPP
  - Existing/planned devices cannot demonstrate integrated CFPP core+edge
- Device designed around modular divertor with space and access for different types of solid/liquid divertors, first-wall, LM plumbing
- Unique hot-wall capability to vary first wall boundary conditions
  - Controlled liquid metal studies, impact of retention / permeation / migration
  - Very high τ_E may require low(er) recycling from liquid Li-wall pumping (?)
- Platform for technology integration: liquid metals, steady-state power-handling, current-drive, control, disruption avoidance
- Develop techniques for very-long-pulse erosion mass removal
- Combine with high core performance to develop confidence to proceed to long-pulse nuclear operations in FNSF/CFPP

Backup

JT-60SA / low n_e SHPD and ITER bracket ρ^* and ν^* expected in CFPPs



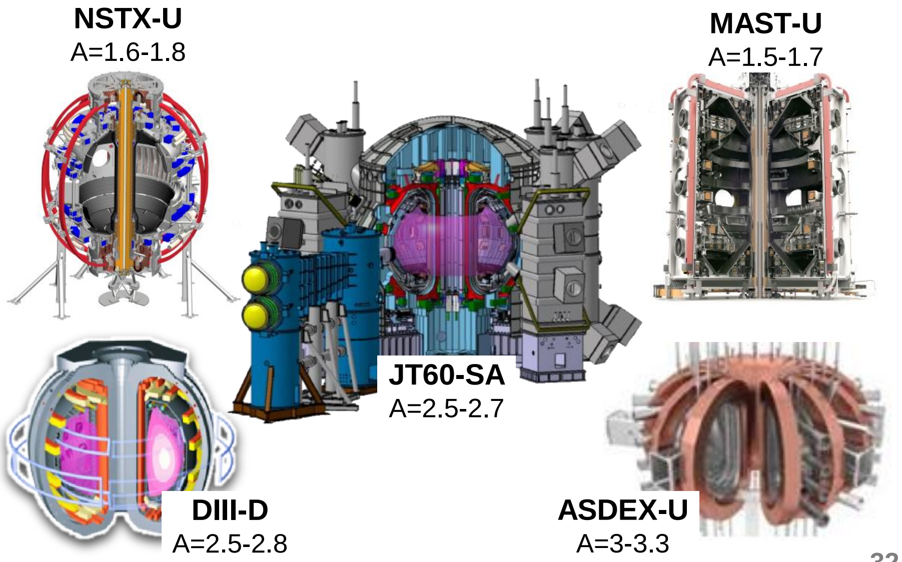
Gap 6: Using high-current-density superconducting coils → compact pilot plant optimal aspect ratio A ~ 2 to 3



R = 3m
TBR ~ 1
P_{NBI} = 50MW
100% non-inductive
β_N (A) at no-wall limit

J.E. Menard, "Compact steady-state tokamak performance dependence on magnet and core physics limits." (2019) Phil. Trans. R. Soc. A 377: 20170440.

- Private industry R&D on HTS TF, PF
- NSTX-U, MAST-U, JT-60SA, DIII-D, AUG span this A range and can inform the integrated core scenarios and advanced divertor physics



Technical motivations for this study

- Utilizing high-Z solid (such as W) PFCs in Pilot Plant has risks:
  - Material damage from melting, erosion and re-deposition, and neutrons
  - High-Z impurity accumulation, associated core plasma radiative collapse
  - Thermal pedestal energy confinement reduction (from increased gas puff?)
  - Compatibility with no-ELM, elevated H_{98}, full non-inductive not established

- Liquid metal (LM) walls and divertors are increasingly being studied as a possible means of addressing these challenges
  - FESS recently investigated liquid metal divertors for FNSF configuration

- This work → explore sustained high power density tokamak
  - Build upon results from test-stands/Magnum-PSI, LTX, EAST, NSTX-U
  - Emphasis on very-long-pulse liquid metal divertor / first-wall viability

Is a(nother) dedicated toroidal facility needed?

- Gaps to Compact Fusion Pilot Plant (CFPP) being identified and quantified in APS-DPP community planning process (CPP)
- Ability of existing, planned (near-term), and upgraded facilities to narrow gaps to CFPP is under discussion
- Is step from existing / planned facilities to Fusion Nuclear Science Facility (FNSF) / CFPP **too large?**
- A counter argument: Dedicated DD facility as pre-requisite to CFPP will cause significant delay, add to overall cost
  - But, hypothetically, if resources are available for fully nuclear CFPP, then parallel satellite DD facility for more rapid accompanying R&D possible?

Science and technology pre-requisites / **Gaps** for a steady-state Compact Fusion Pilot Plant (CFPP)

Abbreviated / simplified summary of Key Gaps (1-4):

1. Access / understand reliable sustainment of enhanced energy confinement
   - Steady-state CFPPs (STPP, ARC) assume H_{98} ~ 1.5-2 accessible and sustainable

2. Demonstrate efficient external non-inductive current-drive
   - Steady-state CFPPs need ≥ ~60-70% bootstrap, remainder from RF and/or NBI-CD

3. Demonstrate pilot-relevant power and particle exhaust handling
   - CFPP $P_{sep}B_T$ / R ~ 100-300 MW T/m ($q_{||}$~10-20GW/m^2, depends on λ_q scaling used)

4. Operate w/ pilot-relevant first-wall, in-vessel components, maintenance
   - CFPP n-fluence, T retention requirements incompatible with carbon PFCs
   - Pilot-level core scenarios not yet achieved with metal walls - tokamak or stellarator

Demonstrating integrated solution to Gaps 1-4 is major challenge

Science and technology pre-requisites / **Gaps** for a steady-state Compact Fusion Pilot Plant (CFPP)

Abbreviated / simplified summary of Key Gaps (5-7):

5. Avoid / mitigate transient events that might damage facility components
   - Prediction, demonstration of ITER ELM control can also be leveraged for CFPP
   - CFPP $W_{magnetic}$ and $W_{thermal}$ similar to ITER → leverage ITER for CFPP
   - Runaway electrons incompatible with thin first-walls needed for efficient T breeding
     - Risk of runaway first-wall penetration, coolant channel damage – tokamak show-stopper?

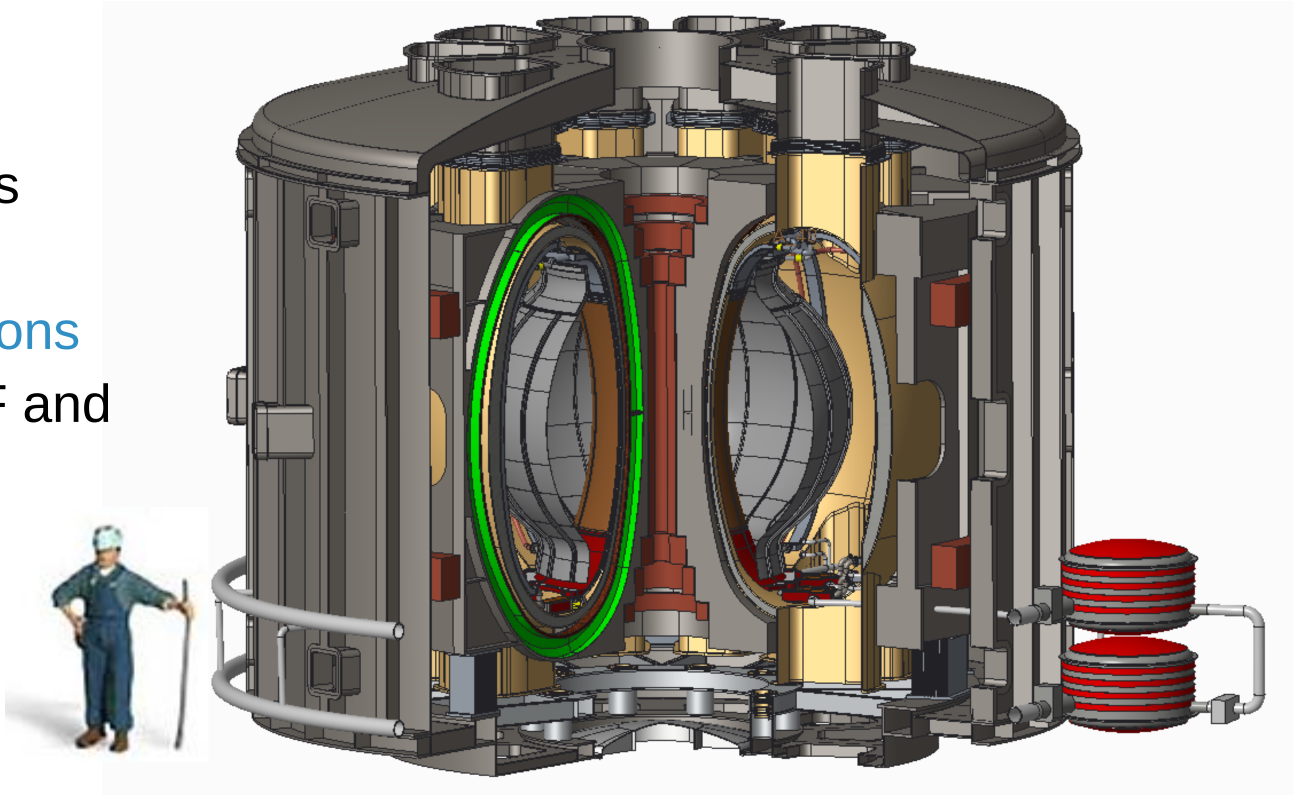
6. Develop high-current-density and high-field toroidal field magnets
   - CFPP requires winding pack current density $J_{WP} \geq 40 MA/m^2$ (2× ITER), B_{coil}=17-23T

7. Develop fusion-nuclear components for pilot-relevant performance
   - Need blankets with high thermal conversion efficiency and tritium breeding ratio
   - CFPP could / should first demonstrate net electric and T self-sufficiency
   - Follow-on with Fusion Nuclear Science (FNS) mission
     - High neutron fluence ≥ 6 MWy/m^2 for materials and component testing

Example configuration developed (R=1m, A=2.4)

Key features:

- Study range of divertors
  - Fast-flow, slow-flow, vapor box, combinations
- High current density TF and inboard PF coils
- Double null divertor
- Vertical maintenance
- ~5T field on axis



Ongoing: Exploring R=1-2m, assess ability to scan range of A=2-2.6 in single device through reconfiguration of in-vessel components

Role of facilities in closing boundary gaps

Parameter / Device	NSTX-U I_P=2MA	NSTX-U I_P=1MA	DIII-D I_P=2MA	DIII-D I_P=1MA	JT-60SA (Inductive)	JT-60SA (Fully Non-Inductive)	Divertor Test Tokamak (Italy DTT)	SPARC	SHPD R=1.2m H_{98}=1.8	SHPD R=1.2m H_{98}=1.0	Low-A Pilot Plant	ARC
Aspect Ratio A	1.7	1.7	2.8	2.8	2.5	2.7	3.1	3.3	2.4	2.4	2.0	3.0
P_{sep} [MW]	12.7	12.7	16.7	16.7	27.3	24.7	32.0	30.0	33.3	33.3	100.0	95.3
B_T [T]	1	1	2.1	2.1	2.25	1.72	6	12	5.3	5.3	4	9.2
R_0 [m]	0.94	0.94	1.6	1.6	2.96	2.97	2.15	1.65	1.2	1.2	3	3.3
I_P [MA]	2.0	1.0	2.0	1.0	5.5	2.3	6.0	7.5	4.3	2.1	12.5	7.8
a [m]	0.55	0.55	0.58	0.58	1.18	1.11	0.70	0.50	0.50	0.50	1.50	1.10
κ_{95}	2.25	2.25	1.89	1.89	1.72	1.83	1.71	1.71	2.19	2.19	2.25	1.66
$\langle B_p \rangle$ [T]	0.39	0.20	0.43	0.21	0.62	0.27	1.19	2.07	0.99	0.49	0.90	0.97
$B_{p\text{-}mp}$ [T]	0.72	0.36	0.78	0.39	1.12	0.50	2.16	3.77	1.81	0.90	1.64	1.76
$\lambda_{q\text{-}int}$ [mm]	3.41	7.79	3.11	7.09	2.00	5.30	0.92	0.47	1.14	2.61	1.27	1.18
$q_{\|\|0}$ [GW / m^2]	1.3	1.2	2.2	1.9	2.2	1.3	10.8	29.5	17.3	15.1	15.4	31.1
$q_{\perp 0}$ [MW / m^2] ($\theta_B = 2^o$)	46	41	76	67	78	46	378	1029	604	529	537	1084
f_{BS}	0.48	0.90	0.52	0.92	0.32	0.76	0.19	0.28	0.70	0.83	0.73	0.63
$\langle p \rangle$ [MPa]	0.065	0.030	0.104	0.046	0.129	0.061	0.307	1.432	0.707	0.208	0.557	0.675
n_{GW} [10^{20}m^{-3}]	2.10	1.05	1.89	0.95	1.26	0.59	3.90	9.55	5.47	2.72	1.77	2.05
Projected c_N for detachment	1.9%	3.9%	3.6%	7.2%	5.0%	8.9%	3.1%	1.7%	2.2%	4.3%	6.6%	12.2%

- NSTX-U: Liquid metal on high-Z solids ($q_\perp \geq$ ~40MW/m^2) at high f_{BS}
- Lower-I_P JT-60SA & DIII-D: Access CFPP-relevant detachment regimes
- Italian DTT and SPARC access CFPP-relevant $q_{\|\|}$, pressure in pulsed operation
- R=1.2m SHPD, P_{heat} = 50MW: sustain integrated CFPP-level $q_{\|\|}$, pressure, f_{BS}

Current LM options under investigation

- Capillary restrained LM (slow flow) surfaces designed for the inboard and outboard FW
- Vapor box divertor located at top incorporating slow flow LM surfaces – with no pumping
- Fast-flow divertor system defined at lower divertor where pumping will occur